Simulation beyond the nuSTORM Production Straight

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Parameters and Variables

Parameters

Parameter	Description	Value
Circumference	Storage ring circumference	616 m
PrdStrghtLngth	Length of production straight	180 m
pAcc	Momentum acceptance	15%
epsilon	Transverse acceptance (2D)	1 pi mm rad
beta	Transverse beta function	25000 mm
HallWallDist	Distance from end of straight to detector hall	50 m
DetHlfWdth	Detector half width	2 m
DetLngth	Detector length	4 m
Hall2Det	Distance from hall wall to detector entrance	5 m
ArcLen	Arc length	128 m

Muon Storage Ring

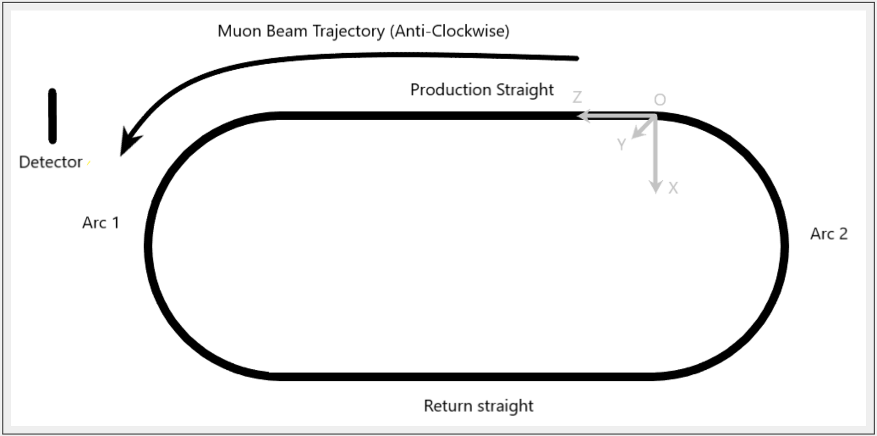


Figure: Muon Storage Ring

Variables

Variable	Description
s	Longitudinal distance travelled by the muon along the storage ring axis
where	Longitudinal position of the muon decay along the storage ring axis measured anti-clockwise from the beginning of the production straight.
r	Radius of the arc
θ	Angle between the longitudinal direction along the storage ring axis and the Z axis of nuSTORM reference frame
Xb, Yb, Zb	Muon beam position at the instant of decay in nuSTORM reference frame
Pb	Longitudinal momentum of a muon in the muon beam (Beam Momentum)
Xt, Yt	Transverse displacement of muons from the beam position (center of the storage ring)
Xm, Ym, Zm	Position of muon decay
Xdmax, Xdmin, Ydmax, Ydmin	Coordinates specifying the dimensions of the detector
Xd, Yd Zd	Coordinates of the point at which a decay product hits the detector plane

Algorithm for Determining Muon Decay Coordinates

Step 1: Determine where the muon decay occurs based on the longitudinal distance travelled.

where = s mod Circumference.

Case 1: PrdStrghtLngth >= where >=0 : The muon decay occurs in the production straight.

Case 2: PrdStrghtLngth + ArcLen >= where >= PrdStrghtLngth : The muon decay occurs in the first arc.

Case 3: 2 PrdStrghtLngth + ArcLen >= where >= PrdStrghtLngth + ArcLen : The muon decay occurs in the return straight.

Case 4: 2 PrdStrghtLngth + 2 ArcLen >= where >= 2 PrdStrghtLngth + ArcLen : The muon decay occurs in the second arc.

Step 2: Calculate the angle between the storage ring axis and Z axis of nuSTORM reference frame.

Production straight:
θ = 0

First Arc:
Distance covered along the arc = where - PrdStrghtLngth
θ = (where - PrdStrghtLngth)/r

Return Straight:
$\theta = \pi$

Second Arc:
Distance covered along the arc = where - 2 PrdStrghtLngth - ArcLen
$\theta = \pi$ + (where - 2 PrdStrghtLngth - ArcLen)/r

Position Coordinates of the Beam

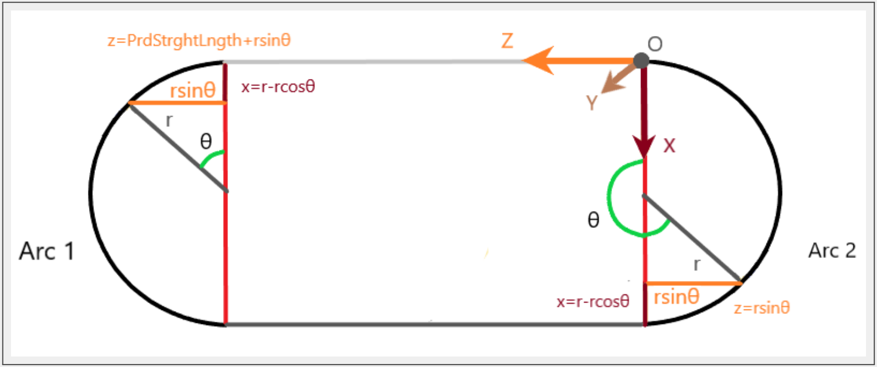


Figure: Position Coordinates of the Beam

Step 3: Calculate the corresponding nuSTORM reference frame position coordinates.

Production Straight:
(Xb, Yb, Zb) = (0, 0, where)

Arc 1:
(Xb, Yb, Zb) = (r- r $cos\theta$, 0, PrdStrghtLngth + r $sin\theta$)

Return straight:
(Xb, Yb, Zb) = (2r, 0, PrdStrghtLngth - (where - ArcLen - PrdStrghtLngth))

Arc 2:
(Xb, Yb, Zb) = (r - r $cos\theta$, 0, r $sin\theta$)

Step 4: Calculate the corresponding nuSTORM reference frame momentum coordinates.

$(Pb_x, Pb_y, Pb_z) = (Pb\ cos\theta, 0, Pb\ sin\theta)$

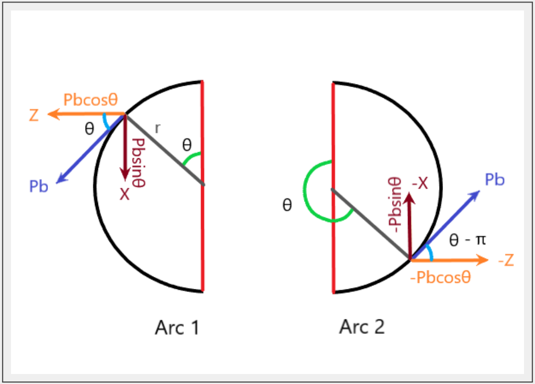


Figure: Beam Momentum Coordinates

Step 5: Obtain the transverse coordinates (Xt, Yt) from the storage ring axis due to beam divergence.

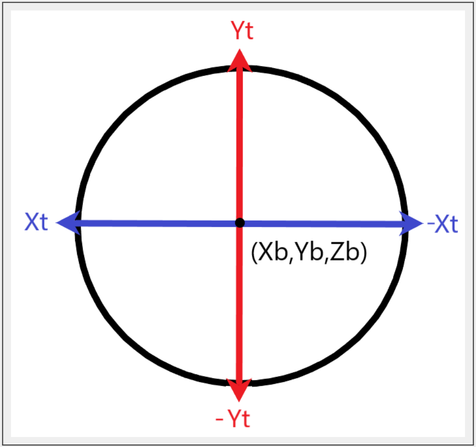


Figure: Cross Section View of the Storage Ring

Step 6: Combine the transverse position coordinates with beam position coordinates to obtain muon decay position coordinates.

$Xm = Xb + Xt\ cos\theta$, $Ym = Yb + Yt$, $Zm = Zb - Xt\ sin\theta$

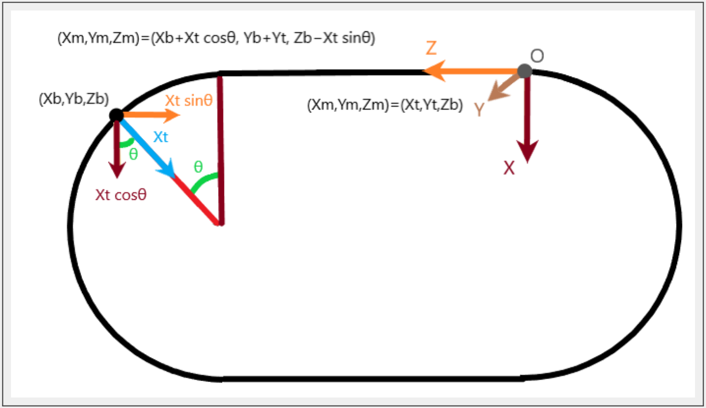


Figure: Muon Decay Position Coordinates

Step 7: Combine the transverse momentum coordinates with beam momentum coordinates to obtain muon decay momentum coordinates.

This step is not necessary for the current approximation.

Testing the Coordinate Calculations

Position Coordinates

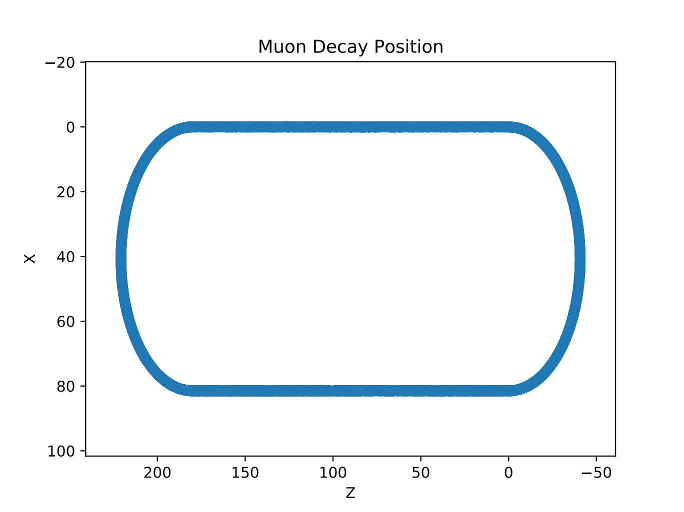


Figure: Scatter Plot of Decay Position Coordinates for 10000 events

Beam Momentum

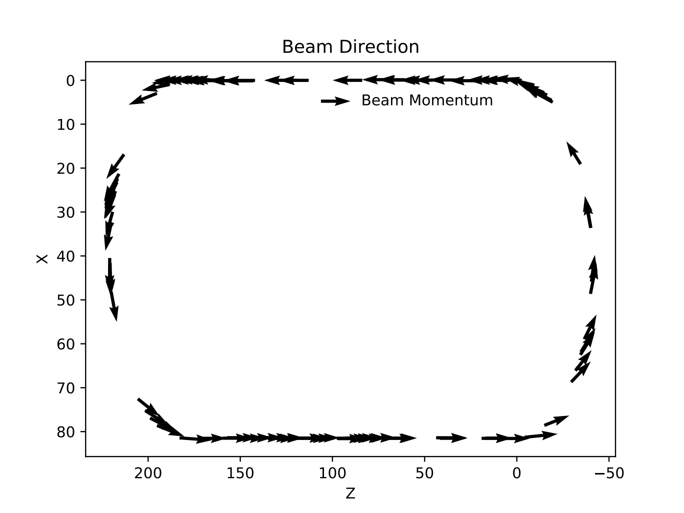


Figure: Beam Momentum Vectors for 100 Events

Algorithm for Determination of Decay Product Momentum

Decay Product Momentum Calculation

Step 1: Determine where the muon is based on the longitudinal position.

Step 2: Obtain the calculated muon momentum 3-vector and determine the beam direction

Step 3: Boost the decay product momentum vectors from muon rest frame to the beam direction in the nuSTORM reference frame.

Electron Momentum

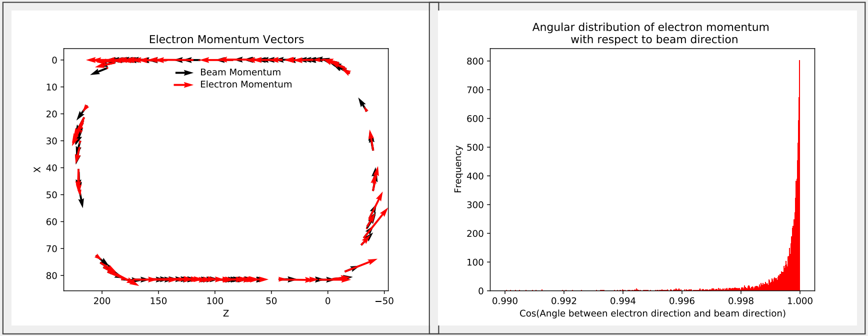
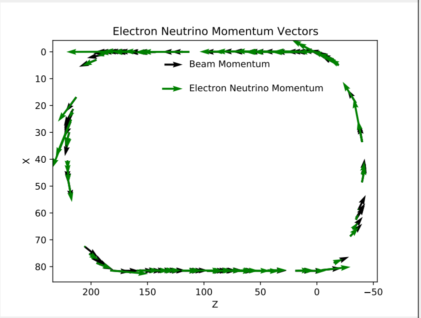


Figure: Electron Momentum Vectors and Angular Distribution

Electron Neutrino Momentum



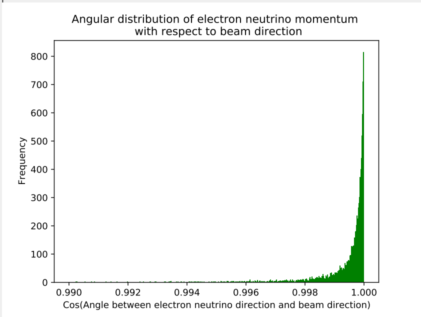


Figure: Electron Neutrino Momentum Vectors and Angular Distribution

Muon Neutrino Momentum

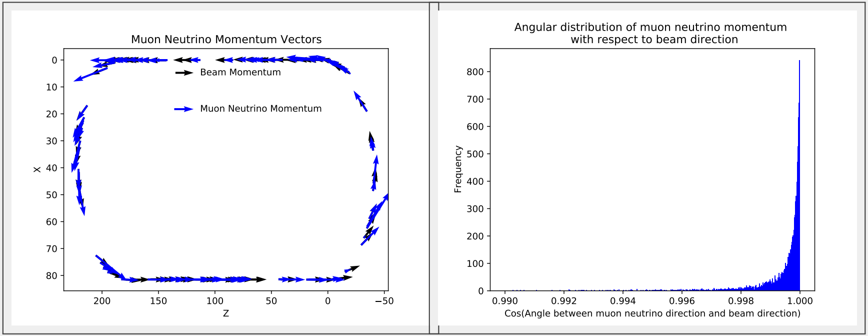


Figure: Muon Neutrino Momentum Vectors and Angular Distribution

Algorithm for Detection of Decay Products

Detection of Decay Products

Step 1: Calculate the coordinates of the detector.
Xdmax = DetHlfWdth; Xdmin= - DetHlfWdth;
Ydmax = DetHlfWdth; Ydmin = - DetHlfWdth;
Zd = PrdStrghtLngth + HallWallDist + Hall2Det

Step 2: Obtain the muon decay position coordinates (Xm, Ym, Zm) and the decay product 3-momentum (Px, Py, Pz).

Detection of Decay Products

Step 3: Find the equation of the straight line through the muon decay position and along the momentum vector direction.

$X = X_m + l\,t$

$Y = Y_m + m\,t$

$Z = Z_m + n\,t$

where l, m and n are the direction cosines corresponding to the vector (Px, Py, Pz)

Step 4: Obtain the value of the parameter t for the detector plane Zd.

$t = (Z_d - Z_m)/n$

Detection of Decay Products

Step 5: Calculate the coordinates of the point at which the decay product hits the detector plane.

$Xd = Xm + l\,t$

$Yd = Ym + m\,t$

Step 6: Check if the decay product is detected.

If $t > 0$ and $Xdmax \geq Xd \geq Xdmin$ and $Ydmax \geq Yd \geq Ydmin$, the decay product is detected.

Estimation of Background Radiation

Estimation of Background Radiation

Run No.	1 round trip	10 round trips	Unlimited round trips
1	1.97	2.63	2.05
2	2.09	1.80	2.47
3	1.31	1.97	1.96
4	1.86	1.59	1.41
5	2.74	2.09	2.28
6	2.34	1.99	1.82
7	2.42	2.03	2.31
8	1.69	1.86	2.25
9	2.56	2.07	1.92
10	2.01	2.02	2.23
Mean S.D.	2.101 $\pm$0.429	2.005 $\pm$0.267	2.070 $\pm$0.309

Table: Percentage of Background Neutrinos for 10000 Events

Estimation of Background Radiation

Run No.	1 round trip	10 round trips	Unlimited round trips
1	1.85	2.03	2.08
2	1.87	2.00	1.61
3	1.94	1.69	1.89
4	1.97	2.03	2.16
5	2.31	1.98	2.08
6	2.04	2.15	2.07
7	2.16	1.76	1.65
8	2.07	2.24	2.73
9	1.99	2.05	2.17
10	2.05	1.71	1.95
Mean S.D.	2.025 $\pm$0.137	1.964 $\pm$0.184	2.038 $\pm$0.313

Table: Percentage of Background Neutrinos for 20000 Events

Estimation of Background Radiation

The pooled mean and standard deviation of the collected data are 2.034%±0.289%. The maximum and minimum values are 2.74% and 1.31%.

We can conclude that the percentage of background neutrinos in the detector lies between 1% and 3% and the average is approximately 2%.

References

- NUSTORM.
  https://github.com/ImperialCollegeLondon/nuSTORM, 2021.
- **Omar Ibna Nazim.**
  Simulation beyond the nustorm production straight.
  https://cds.cern.ch/record/2777280.